More on Non-standard Interaction at MINOS

Hiroaki Sugiyama

SISSA, Via Beirut 2-4, 34014 Trieste, Italy

Abstract. We discuss about effects of the non-standard interaction of neutrinos with matter on the ν_e appearance search in the MINOS experiment. We consider the effects of the complex phase of the interaction and of the uncertainty on θ_{23} also. We show that the oscillation probability can be so large that can not be explained by the ordinary oscillation. We show also how much constraints on the non-standard effects can be improved if the experiment does not observe ν_e appearance signal.

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INTRODUCTION

Oscillations of three generation neutrinos are parametrized by two mass squared differences, three mixing angles, and one CP violating phase. Among these parameters, a tiny mixing angle θ_{13} and the phase δ have not been measured yet. Measuring tiny effects of θ_{13} and δ is the main purpose of future oscillation experiments. On the other hand, such precision measurements will be sensitive to effects of new physics also. In this talk, we investigate possibilities to see new physics effects on the ν_e appearance search with ν_μ beam in the MINOS experiment [1]. This talk is based on [2].

We consider the non-standard interaction (NSI) of neutrinos with matter as an example of new physics. The interaction is introduced in a model-independent way by the following effective Lagrangian

$$\mathscr{L}_{\rm eff} = \varepsilon_{\alpha\beta}^{fP} G_{\rm F} (\overline{\nu_\alpha}\gamma_\mu P_L \nu_\beta)(\overline{f}\gamma^\mu P f), \qquad (1)$$

where α $(= e, \mu, \tau)$ and β stand for flavors, $G_{\rm F}$ is the Fermi coupling constant, P $(= P_L, P_R)$ denotes the projection operator onto the left-handed one or the right-handed one, and f $(= e, u, d)$ represents the fermions existing in matter. Then, the Hamiltonian in the flavor basis is modified from the standard one and it is given by

$$H = \frac{1}{2E} U_{\rm MNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U_{\rm MNS}^\dagger + A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}, \qquad (2)$$

where $A \equiv \sqrt{2} G_{\rm F} n_e$ with the electron number density n_e, and $\varepsilon_{\alpha\beta} \equiv \sum_P (\varepsilon_{\alpha\beta}^{eP} + 3\varepsilon_{\alpha\beta}^{uP} + 3\varepsilon_{\alpha\beta}^{dP})$. The first term of the right hand-side of (2) is for the oscillation in vacuum and the second term is the matter potential with NSI. In this talk, a typical matter density $\rho = 2.7 {\rm g} \cdot {\rm cm}^{-3}$ is used and then we have $A \simeq 10^{-13}$eV. On the other hand, the size of the vacuum part of the Hamiltonian are controlled by $\Delta m^2/2E$, and it is $\sim 10^{-13}$eV for the MINOS experiment. Thus, we expect some NSI effect in the MINOS experiment if $\varepsilon_{\alpha\beta}$ can be ~ 1.

CONSTRAINTS ON $\varepsilon_{\alpha\beta}$

Experiments involving charged leptons strongly bound the effective interaction (1) if $SU(2)_L$ symmetry is imposed. From a model independent point of view, however, the strength $\varepsilon_{\alpha\beta}^{fP}$ of the interaction (1) can be independent of the strength of the charged lepton version of (1) because we know $SU(2)_L$ is broken. Therefore, $\varepsilon_{\alpha\beta}^{fP}$ can be constrained only by experiments with neutrinos. [1] Using the results obtained in [3], we have constraints on the elements of (2). We put $|\varepsilon_{e\mu}| = \varepsilon_{\mu\mu} = |\varepsilon_{\mu\tau}| = 0$ because they are constrained enough. The constraints on ε_{ee} and $|\varepsilon_{e\tau}|$ are

$$-4 < \varepsilon_{ee} < 2.6, \quad |\varepsilon_{e\tau}| < 1.9. \qquad (3)$$

The constraint on $\varepsilon_{\tau\tau}$ in [3] is rather loose but it is improved by the atmospheric neutrino measurement and the K2K experiment [4]. In order to reproduce the observed ν_μ disappearance for $\Delta m_{21}^2 = 0$ and $\theta_{13} = 0$, which is $1 - P(\nu_\mu \to \nu_\mu) = \sin^2 2\theta_{23}^{\rm obs} \sin^2((\Delta m_{31}^2)^{\rm obs} L/4E)$, the parameters in vacuum (θ_{23}, Δm_{31}^2) and non-standard in-

[1] Actually, constraints on $\varepsilon_{\alpha\mu}^{fP}$ are obtained by experiments with muon through loop effects.

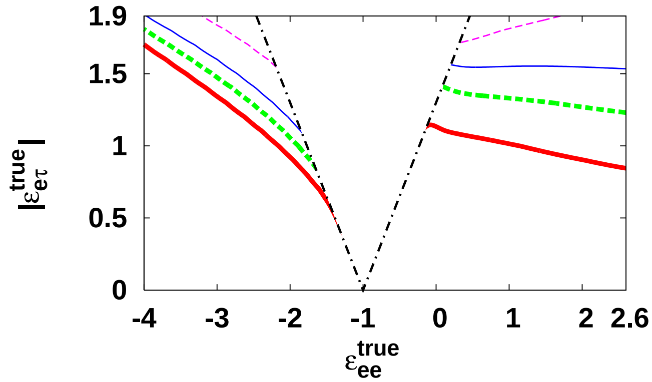

FIGURE 1. Thin dashed, thin solid, bold dashed, and bold solid curves are obtained for $\sin^2 2\theta_{13}^{\text{true}} = 0, 0.05, 0.1$, and 0.16, respectively. If true values exist above these curves, the MINOS experiment can see the NSI effect. The region above the dash-dotted line has been excluded by the atmospheric neutrino measurement and the K2K experiment.

teractions should satisfy

$$\varepsilon_{\tau\tau} = \frac{|\varepsilon_{e\tau}|^2}{1+\varepsilon_{ee}}, \tag{4}$$

$$\cos 2\theta_{23} = \frac{s_\beta^2(1+c_\beta^2) + 4c_\beta^2 \cot 2\theta_{23}^{\text{obs}} \sqrt{(1+\cot^2 2\theta_{23}^{\text{obs}})}}{(1+c_\beta^2)^2 + 4c_\beta^2 \cot^2 2\theta_{23}^{\text{obs}}}, \tag{5}$$

$$\Delta m_{31}^2 = \frac{2\left(\Delta m_{31}^2\right)^{\text{obs}}}{\sqrt{\{(1+c_\beta^2)\cos 2\theta_{23} - s_\beta^2\}^2 + 4c_\beta^2 \sin^2 2\theta_{23}}}, \tag{6}$$

where $\tan\beta \equiv |\varepsilon_{e\tau}|/(1+\varepsilon_{ee})$, c_β and s_β denote $\cos\beta$ and $\sin\beta$, respectively. Furthermore, in order to be consistent with the sub-GeV data of atmospheric ν_μ, where the matter effect is suppressed, the parameters in vacuum should satisfy

$$\cos 2\theta_{23} < 0.5, \quad |\Delta m_{31}^2| < 5\times 10^{-3}\text{eV}^2. \tag{7}$$

The conditions give an upper-bound on $|\tan\beta|$, and then we can constrain $\varepsilon_{\tau\tau}$ also as $|\varepsilon_{\tau\tau}| < |\tan\beta|^{\max}|\varepsilon_{e\tau}|^{\max}$. We use the conditions (4)-(7) for also the case with $\Delta m_{21}^2 \neq 0$ and $\theta_{13} \neq 0$ for simplicity.

ANALYSES AND RESULTS

In our analysis, we calculate numbers of ν_e events (signal and background) for 13 bins of 0.5GeV width within 1-7.5GeV of the reconstructed energy. We assume 16×10^{20}POT which corresponds to about 5 years of running. Systematic errors are ignored for simplicity. Two parameters are fixed as $\sin^2 2\theta_{12} = 0.8$, $\Delta m_{21}^2 = 8\times 10^{-5}\text{eV}^2$ throughout this talk.

First, we investigate the possibility to see the effect of NSI in the MINOS experiment. "Data" are generated with NSI and we try to fit the "data" without NSI. If the $\Delta\chi^2$ that corresponds to the fitting is larger than 4.6, it means that the MINOS experiment can exclude the case with $\varepsilon_{ee} = |\varepsilon_{e\tau}| = 0$ and see the NSI effect at 90%CL. [2] For the generation of the "data" with NSI, we use

$$\delta^{\text{true}} = \arg(\varepsilon_{e\tau}^{\text{true}}) = 0, \tag{8}$$

$$s_{23}^{\text{true,obs}} = 1/\sqrt{2}, \quad (\Delta m_{31}^2)^{\text{true,obs}} = 2.7\times 10^{-3}\text{eV}^2. \tag{9}$$

We fix $\sin^2 2\theta_{13}^{\text{true}}$ also but take several values for that. On the other hand, the values of parameters for fitting without NSI are

$$0 \le \sin^2 2\theta_{13} \le 0.16, \tag{10}$$

$$\delta = -\pi/2, \quad s_{23} = 0.8\ (\sin^2 2\theta_{23} = 0.92), \tag{11}$$

$$\Delta m_{31}^2 = 2.7\times 10^{-3}\text{eV}^2. \tag{12}$$

$\Delta\chi^2$ is minimized with respect to θ_{13} within the region. Note that the choice of (11) is for large $P(\nu_\mu \to \nu_e)$ in the standard oscillation, and hence it is a pessimistic one for the search of the NSI effect. The result is shown in Fig. 1. The region above the dash-dotted line has

[2] Since pure information about θ_{13} can be obtained in the future reactor experiments, we try to extract information about ε_{ee} and $|\varepsilon_{e\tau}|$ only. Therefore, we rely on the analysis for 2 degrees of freedom in which $\Delta\chi^2 = 4.6$ corresponds to 90%CL. If we try to extract information about θ_{13} also, we should use the analysis for 3 degrees of freedom and then the results get worse with $\Delta\chi^2 = 6.3$.

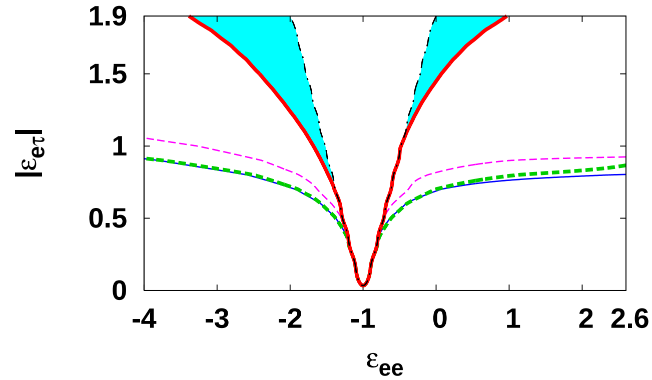

FIGURE 2. The results for the case without ν_e appearance signal are shown. The region above the dash-dotted line has been excluded by the atmospheric neutrino measurement and the K2K experiment. Additionally to that, the gray region can be excluded by the MINOS experiment.

been excluded by $|\tan\beta| < 1.3$ obtained with (7) and (9). The thin dashed, thin solid, bold dashed, and bold solid curves are results for $\sin^2 2\theta_{13}^{\rm true} = 0, 0.05, 0.1$, and 0.16, respectively; If nature chooses true values above the curves, the number of ν_e appearance signal becomes so large that cannot be explain with θ_{13} only. Then, it is possible to see the NSI effect in the MINOS experiment.

Next, let us consider the case without ν_e appearance signal. In this case, bounds on ε will be obtained by the search. "Data" for the analysis is generated by

$$\theta_{13}^{\rm true} = \varepsilon_{ee}^{\rm true} = |\varepsilon_{e\tau}^{\rm true}| = 0, \tag{13}$$

$$s_{23}^{\rm true} = 1/\sqrt{2}, \quad (\Delta m_{31}^2)^{\rm true} = 2.7 \times 10^{-3} {\rm eV}^2, \tag{14}$$

and we try to fit the "data" by using NSI. If the fitting is failed, we can exclude the values of ε. For the fitting procedure, we use

$$0 \le \sin^2 2\theta_{13} \le 0.16, \tag{15}$$

$$\delta = 0, \quad \arg(\varepsilon_{e\tau}) = 0, \pi/2, \pi, -\pi/2, \tag{16}$$

$$s_{23}^{\rm obs} = 0.6, 1/\sqrt{2}, 0.8, \tag{17}$$

$$(\delta m_{31}^2)^{\rm obs} = 2.7 \times 10^{-3} {\rm eV}^2. \tag{18}$$

Note that phases appear as $\delta + \arg(\varepsilon_{e\tau})$ approximately, which is exact for $\Delta m_{21}^2 = 0$, and then we can put $\delta = 0$. $\Delta\chi^2$ for this analysis is minimized with respect to θ_{13} and three values of $s_{23}^{\rm obs}$. The smallest and the largest values of $s_{23}^{\rm obs}$ are obtained from $\sin^2 2\theta_{23}^{\rm obs} = 0.92$. In Fig. 2, results for $\arg(\varepsilon_{e\tau}) = 0, \pi/2, \pi$, and $-\pi/2$ are shown by thin dashed, thin solid, bold dashed, and bold solid curves. The region bellow the curves can be consistent with the case of no ν_e appearance at 90%CL, and then we should take the bold solid curve as a pessimistic choice for the exclusion of ε in the MINOS experiment. The dash-dotted line is given by (7) and the region above the line has been excluded by atmospheric neutrino measurement and the K2K experiment. Hence, the gray region shows the possible improvement of the bound on ε in the MINOS experiment.

CONCLUSIONS

We have investigated possibilities to obtain information about NSI effect with the search of $\nu_\mu \to \nu_e$ oscillation in the MINOS experiment. We have shown that it is possible to find the effect in the experiment. Even if the experiment does not find ν_e appearance signal, some part of ε_{ee}-$\varepsilon_{e\tau}$ space can be excluded by the result. Therefore, ongoing and future oscillation experiments are very interesting not only for the precise determination of the mixing parameter in the lepton sector but also for the new physics search.

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